DEMONSTRATION REPORT

Data Collection with Vehicular-Based Systems - Pole Mountain, WY

ESTCP Project MR-201160

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Stephen Billings
Sky Research, Inc.

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EXECUTIVE SUMMARY

This demonstration report describes the data collection, processing and analysis of cued-interrogation data collected with Sky Research's SKY3D vehicular platform at the Pole Mountain Target and Maneuver Area (PMTMA), near Laramie, WY. SKY3D integrates a MetalMapper sensor, real-time-kinematic global positioning system and inertial measurement unit (in the form of the Novatel SPAN) and a custom user interface on a Kubota all-terrain-vehicle. Cued interrogation data were collected by dwelling for 30 seconds over 2,370 anomalies previously identified via a full-coverage geophysical survey of part of the Bisbee Area of PMTMA.

The data collection was conducted in the field over a 14 day period in July and August 2011. Production rate was as high as 39 points per survey hour with a maximum of 326 anomalies visited in a day. During the first eight field days, an electrical issue with the instrument orientation sensor resulted in a lower average production rate of 21 points per hour. During the last six field days, and after the orientation sensor problem was rectified, the production rate increased 64% to an average of 32 points per hour. Weather and summer thunderstorms impacted two days.

In this demonstration report we evaluate eight identified performance metrics for the technology including four pertaining to the data collection (reliability/robustness, survey rate, percentage of site covered, MetalMapper sensor position accuracy) and four to the subsequent processing and classification of the collected data (percentage of munitions correctly identified, reduction in false-alarm rate, appropriate specification of stop-dig point and minimization of "can't analyze" anomalies). Six of the eight performance objectives were easily achieved, while one objective, 90% of MetalMapper positions within 30 cm of each Target of Interest (TOI), was missed by 1 cm (90^{th} percentile at 31 cm). The last and only qualitative objective on reliability/robustness was only partially met due to the electrical issues with the orientation sensor on the Novatel SPAN.

At the final stop-dig point selected after analysis of the MetalMapper data, 369 anomalies were excavated and all 160 TOI were identified. A total of 209 of the 2210 clutter items were excavated: this meant that 91% of the clutter could have been left in the ground, resulting in significant potential cost savings. During the Pole Mountain demonstration MetalMapper data were collected at 2,370 anomaly locations. Based on the cost information collected as part of this demonstration the per anomaly costs (excluding mobilization and reporting) were

- $41.24 for data collection; and
- $4.08 for data processing.

The total cost per anomaly (for data collection and processing) was $45.52. Using an often quoted rule of thumb that each excavation costs $100, then without deploying the MetalMapper system the excavation costs would have been approximately $237,000. With the MetalMapper only 369 anomalies needed to be excavated at a cost of $36,900. When combined with the MetalMapper mobilization, data collection, processing and reporting costs of $168,270 the cost of clearance using the MetalMapper was $205,170: a saving of $31,830 (or 13%).

Comparing EM61 pick locations versus the actual ground-truth locations of TOI revealed large errors in position and demonstrated the importance of fine-tuning the cued-interrogation location using the (currently limited but functional) real-time position estimation capabilities of the MetalMapper. Nightly quality control of the collected data was another important determinant of cued-interrogation data quality, with 125 anomalies recommended for recollection.

The demonstration was conducted under project ESTCP MR-201160 “Data collection with vehicular based advanced Electromagnetic Induction (EMI) sensors” as part of the wider ESTCP Live Site Demonstrations.

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ACRONYMS

A	Amperes
AC	Alternating Current
AGL	Above Ground Level
ASR	Archive Search Report
B(t)	Time-Varying Secondary Magnetic Field
cm	centimeter
COTS	Commercial Off The Shelf
DAQ	Data Acquisition System
dB	Decibels
DC	Direct Current
DGM	Digital Geophysical Mapping
DMU	Data Management Unit
EM	Electromagnetic
EMI	Electromagnetic Induction
ERDC	Engineer Research and Development Center
ESTCP	Environmental Security Technology Certification Program
FPGA	Field Programmable Gate Array
FUDS	Formerly Used Defense Sites
GPO	Geophysical Prove Out
GPS	Global Positioning System
HE	High Explosive
Hz	Hertz
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
m	meter
m(t)	Target's Polarization Tensor
MEC	Munitions and Explosives of Concern
MINS	Mare Island Naval Shipyard
MR	Munitions Response
ms	Millisecond
µs	Microsecond
NAD	North American Datum
P_d	Probability of Detection
PI	Principal Investigator
PMTMA	Pole Mountain Training and Maneuver Area
ppm	parts per million
PPS	Pulse Per Second
QA/QC	Quality Assurance/Quality Control
QAPP	Quality Assurance Project Plan
r	location
R&D	Research and Development
RMS	Root Mean Square
RTK GPS	Real-time Kinematic Global Positioning System
RTS	Robotic Total Station
SKY	Sky Research, Inc.

SNR	Signal to Noise Ratio
TEM	Time-domain Electromagnetic
TOI	Targets of Interest
US	United States
USACE	United States Army Corps of Engineers
UTM	Universal Transverse Mercator
UXO	Unexploded Ordnance

1.0 INTRODUCTION

1.1 BACKGROUND

The Fiscal Year 2006 Defense Appropriation contains funding for the "Development of Advanced, Sophisticated, Discrimination Technologies for UXO Cleanup" in the Environmental Security Technology Certification Program (ESTCP). In 2003, the Defense Science Board observed: "The problem is that instruments that can detect the buried unexploded ordnance (UXO) also detect numerous scrap metal objects and other artifacts, which leads to an enormous amount of expensive digging. Typically 100 holes may be dug before a real UXO is unearthed! The Task Force assessment is that much of this wasteful digging can be eliminated by the use of more advanced technology instruments that exploit modern digital processing and advanced multi-mode sensors to achieve an improved level of discrimination of scrap from UXO." The discrimination potential of the MetalMapper system has been demonstrated by Research & Development (R&D) staff at the San Luis Obispo demonstration site (Billings et al., 2010) and a second demonstration at Camp Butner (Pasion et al., 2012).

To date, testing of these approaches has been primarily limited to test sites, with only limited application at live sites. Acceptance of discrimination technologies requires demonstration of system capabilities at real UXO sites under real world conditions. Any attempt to declare detected anomalies to be harmless and requiring no further investigation will require demonstration to regulators of not only individual technologies, but an entire decision making process.

To build on this initial R&D success, and ensure that the system is deployed across a wide range of UXO contaminated sites, requires that the system be turned over to experienced production personnel. Sky Research, Inc. (SKY) has a Geophysical Operations Department that undertakes Digital Geophysical Mapping (DGM) operations at multiple sites within the United States (U.S.). SKY has made a commitment to bringing discrimination technologies to production usage by being the first company to purchase a MetalMapper sensor. This project will provide an assessment of the ease (or otherwise) with which the MetalMapper technology can be transitioned to production staff.

1.2 OBJECTIVES OF THE DEMONSTRATION

The demonstration objective is to collect high quality MetalMapper sensor data in a cued interrogation mode over 2,370 anomalies previously detected during an EM61 survey.

The data collection is intended to meet the following objectives:

1. Demonstrate the transition of the new, but now commercially available, MetalMapper sensor to personnel engaged in production data collection (and not involved in research and development).
2. Provide advanced EMI sensor data from the MetalMapper to a wide range of data analysts to test different processing and interpretation methodologies.

2.0TECHNOLOGY DESCRIPTION

EMI is generally considered to be the most promising technology for discriminating between UXO and non-UXO items. In the EMI method, a time varying field illuminates a buried, conductive target. Currents induced in the target then produce a secondary field that is measured at the surface. EM data inversion involves using the secondary field generated by the target for recovery of the position, orientation, and parameters related to the target's material properties and shape. In the UXO community, the inverse problem is usually simplified by assuming that the secondary field can be accurately approximated as a dipole.

Time-domain Electromagnetic (TEM) sensors illuminate a buried target by rapidly turning off a transmitting loop which causes a step-change in the magnetic field below the ground, inducing eddy currents in any metallic objects. The eddy currents induced in the target decay with time, generating a decaying secondary field that is measured at the surface. The time-varying secondary magnetic field B(t) at a location r from the dipole m(t) is:

$$\boldsymbol{B}(t) = \frac{\mu_0}{4\pi r^3}\boldsymbol{m}(t) \cdot (3\hat{\boldsymbol{r}}\hat{\boldsymbol{r}} - \bar{\mathbf{I}})$$

Where $\hat{\boldsymbol{r}} = \boldsymbol{r}/|\boldsymbol{r}|$ is the unit-vector pointing from the dipole to the observation point, I is the 3 x 3 identity matrix, μ_0 = 4 π x 10-7 H/m is the permittivity of free space and r = |r| is the distance between the center of the object and the observation point.

The dipole induced by the interaction of the primary field $\boldsymbol{B_0}$ and the buried target is given by:

$$\boldsymbol{m}(t) = \frac{1}{\mu_0}\bar{\boldsymbol{M}}(t) \cdot \boldsymbol{B}_0$$

where **M**(t) is the target's polarization tensor. The polarization tensor governs the decay characteristics of the buried target and is a function of the shape, size, and material properties of the target. The polarization tensor is written as:

$$\bar{\boldsymbol{M}}(t) = \begin{bmatrix} L_1(t) & 0 & 0 \\ 0 & L_2(t) & 0 \\ 0 & 0 & L_3(t) \end{bmatrix}$$

where we use the convention that $L_1(t_1) \geq L_2(t_1) \geq L_3(t_1)$ so that polarization tensor parameters are organized from largest to smallest. The polarization tensor components are parameterized such that the target response can be written as a function of a model vector containing components that are a function of target characteristics.

ESTCP sponsored discrimination pilot projects at the Former Camp Sibert and San Luis Obispo have demonstrated the ability of advanced EMI sensors to constrain the polarization tensor parameters of buried metallic objects (e.g. Billings et al., 2008, 2010). Attributes such as the size, decay rate and symmetry (or lack thereof) of the polarization tensor parameters provide an indication of the identity of the underlying object. Intelligent classification techniques have demonstrated an impressive ability to produce a prioritized dig-list with most, or all, of the Targets of Interest (TOI) ranked as high-priority excavations.

2.1 METALMAPPER SENSOR

In 2010, SKY purchased the first commercially available MetalMapper sensor. The MetalMapper is a 3-axis transmit, 3-axis receive EMI array developed by G&G Sciences and commercially produced by Geometrics. This array has been incorporated into SKY's UXO discrimination system known as the SKY3D **(**Figures 1 and 2), which comprises an all-terrain survey vehicle, the sensor frame and associated suspension, the MetalMapper advanced sensor, global positioning system (GPS) and inertial measurement unit (IMU) sensors for precise positioning, data acquisition hardware (National Instruments PXI-1031) and software, and discrimination processing software modules. The system completed its first field trial during the summer of 2010 at the ESTCP Live Site Demonstration at Camp Butner in North Carolina.

The MetalMapper sensor head consists of three orthogonal 1-meter square transmitter loops that excite nearby targets with a large-moment magnetic field. The sensor base contains an array of seven small 3-axis receiver cubes that measure the complete vector magnetic field at an optimized distribution of measurement locations. Figure 3 shows the layout of the receiver cubes.

Figure 1. The SKY3D MetalMapper. The SKY3D MetalMapper extended in survey mode (LEFT) and elevated in transport mode (RIGHT).

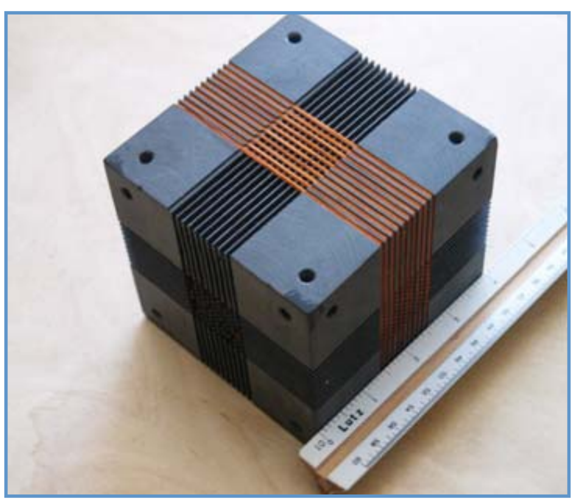


Figure 2. A Close-Up of a MetalMapper Receiver Cube

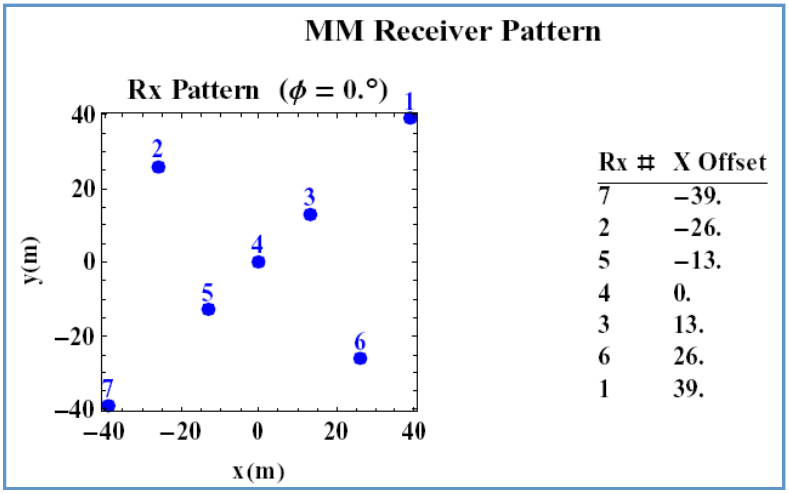


Figure 3. Distribution of Receiver Locations in the MetalMapper Sensor Base.

Each receiver measures the complete vector magnetic field at its location to fully characterize the target response to the impinging transmitter field.

The MetalMapper can be deployed in either "dynamic" mode or in a "cued-interrogation" mode. In the former, data are collected continuously while the vehicle traverses over an area. This mode is primarily intended for detection and utilizes only the z-axis transmitter. Each detection (or a subset of detections if prescreening is applied) is then revisited in turn with the sensor operating in the second, cued-interrogation, mode. The array is approximately centered over the unknown object and data are collected with the system static. In this mode, all three orthogonal transmitters are used, with data collected after excitation of the ground by each transmitter. Note that the MetalMapper could also be cued by an alternative detection sensor such as an EM61.

The combination of orthogonal transmit and receive data yields an extremely rich set of feature vectors that can be used to characterize an anomaly. Specifically, the 3-axis illumination ensures a more accurate recovery of target polarizability parameters than that afforded by vertical axis illumination alone. Discrimination is achieved when an anomaly can be confidently classified as either a TOI or a non-TOI. Usually this decision is based on statistical classification of anomaly features as either target-like or non-target-like. The determination of TOI characteristics versus non-TOI characteristics is achieved through analysis of training data, which comprise the responses of a sample set of targets and clutter that are representative of those expected to be at the survey site. Features for analysis may be extracted from inversion of physics-based forward models or through direct interpretation of the data. Examples of relevant features include the shape of the item as determined by comparison of the primary, secondary, and tertiary polarizations; time decay information based on the decay of the primary polarization; and the size of the object as determined by scaling parameters recovered from inversion of the forward model.

2.2 TECHNOLOGY MATURITY

The MetalMapper is a mature technology that has been tested at the standardized UXO test-sites as well as at the San Luis Obispo and Camp Butner demonstration sites. The SKY MetalMapper

was deployed at the Camp Butner site and was used to collect about half of the cued-interrogation anomalies that were surveyed at that site. Analysis of the data from Camp Butner by Dr. Donald Snyder revealed that the SKY incarnation of the MetalMapper had superior Signal-to-noise Ratio (SNR) characteristics compared to the original Geometrics deployed system: SNR was improved by around 10 decibels (dB). There were a number of contributing factors for this improvement:

1. The SKY system was 7 centimeters (cm) closer to the ground than the Geometrics system
2. The newer preamplifiers and electronics in the SKY system have lower noise than the original system.
3. The SKY vehicle was turned off during data acquisition while the Geometrics vehicle was left running.
4. The Geometrics deployed system suffered from periodic malfunction of two of the receivers.

A number of enhancements were made to the MetalMapper sensor after the Camp Butner deployment including:

- Modified power harness to provide alternating current (AC) and direct current (DC) options and polarity reversal protection. The Data Acquisition System (DAQ) and receiver cubes are powered through an inverter running off two marine deep cycle batteries coupled in parallel. The transmitters are supplied by up to four internal Ultralife batteries coupled in parallel. This power configuration has enough capacity for almost two days of cued interrogation.
- Mounted all electronics (DAQ, inverter, batteries, cables, etc.) in Kubota bed using waterproofed plywood palette and mounting brackets.
- Installed vibration damping material in the sensor head mount to reduce vibration induced noise.
- Replaced winch cable with higher strength Amsteel Blue cable.
- Reinforced winch cable tower with welded gussets to reduce strain on assembly when sensor head is suspended.
- Routed all cables through plastic conduit mounted on sensor frame arms.
- Improved cab mounts for monitor, keyboard, and mouse.
- Reinforced sensor head tray assembly and coated with spar urethane.

2.2.1 Positioning System: Novatel SPAN

A Novatel SPAN system combines a GPS receiver with an Inertial Measurement Unit (IMU). An accurate 3D position, velocity and attitude information is continuously output from the SPAN, even when GPS information becomes unavailable. A Novatel ProPak v3 receiver was mounted in the bed of the tow vehicle with the Novatel IMU-G2-000 IMU and GPS antenna mounted above the center of the sensor coils. Position data was output in a NMEA format at a rate of 20Hz. In cued interrogation mode, one position value was recorded per cued point.

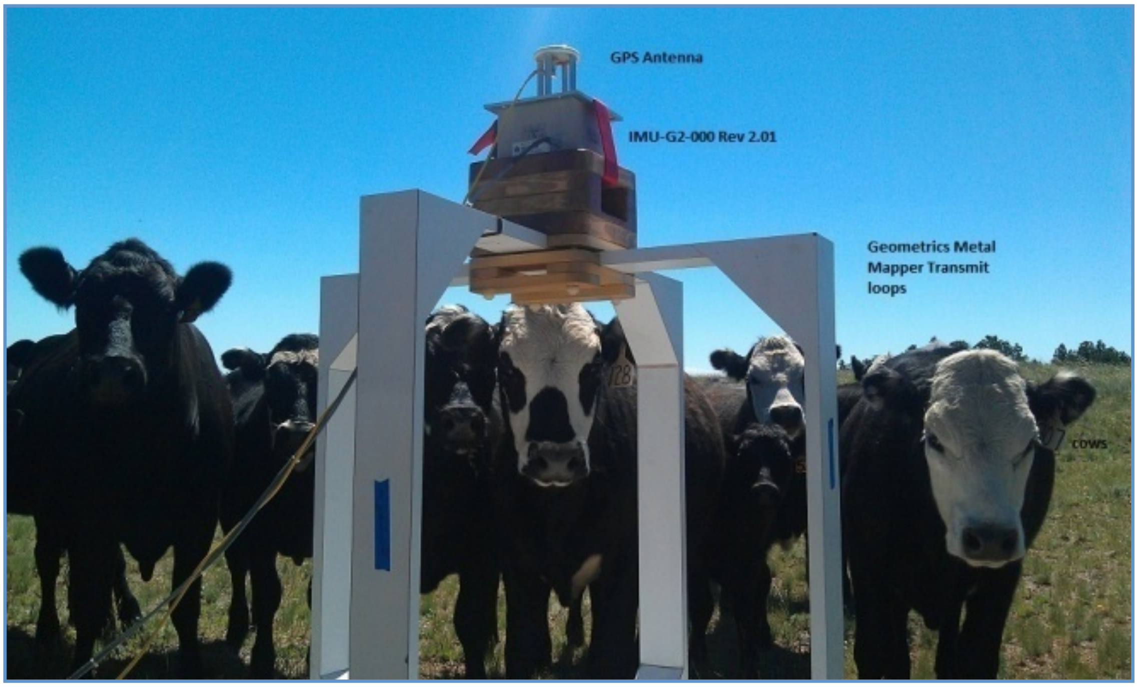


Figure 4 Sky Research utilizes the Novatel Span System.

This device provides position, pitch, heading and roll information.

2.2.2 Data Acquisition System

The data acquisition system (DAQ) is built around a commercially available product from National Instruments. The DAQ and EM transmitter are packaged in an aluminum case that weighs approximately 43 pounds when all four transmitter batteries are installed.

The DAQ is a full-featured PC running Windows 7. It contains disk storage, serial and USB input/output ports, and more. It is interfaced to analog-to-digital converters and to digital input/output devices through its internal PCI bus. It is packaged in an industry standard PXI configuration that is intended for industrial applications. Figure 5 is a functional block diagram of the DAQ instrument package.

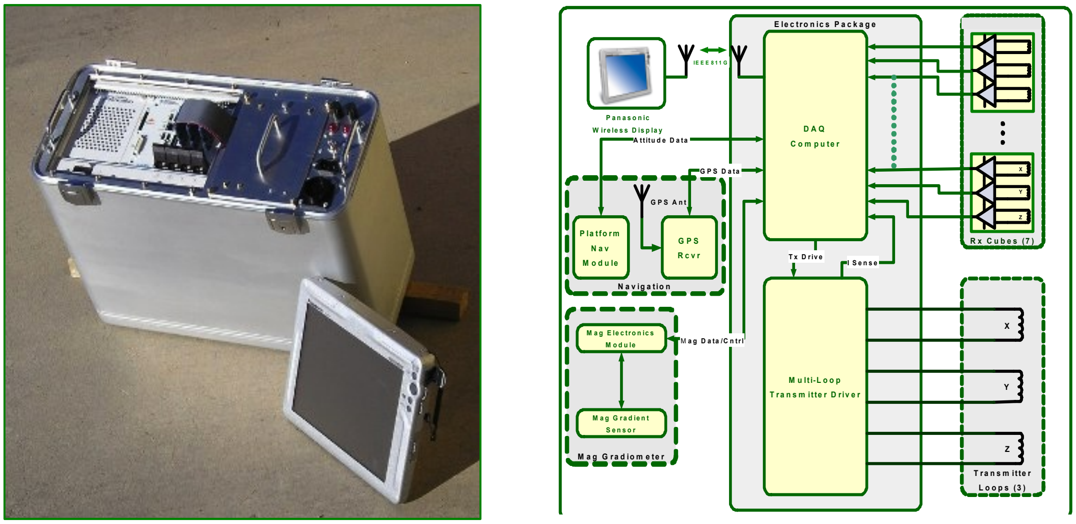
2.3 PREVIOUS TESTING OF THE TECHNOLOGIES

The MetalMapper sensor system, using a different Novatel SPAN, was used by Sky Research at San Luis Obispo and Camp Butner demonstration sites.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGIES

The main limitations of the MetalMapper sensor system in a cued-interrogation mode relate to the equipment and labor costs. Cued-interrogation introduces additional costs in that each selected anomaly has to be visited with a second geophysical survey system. The MetalMapper system also has a limited range of terrain/vegetation that can be accessed by the system.

The additional labor and equipment costs may be offset by reducing the amount of digs preformed by the UXO intrusive team.



A) MM DAQ assembly with Panasonic terminal.

B) Function block diagram of MM system

Figure 5 A) -The MetalMapper (DAQ) and B) Functional Block Diagram

3.0 PERFORMANCE OBJECTIVES

Performance objectives for the demonstration are given in Table 1 to provide a basis for evaluating the performance and costs of the demonstrated technology. These objectives are for the technology being demonstrated only; overall project objectives will be given in the demonstration report to be prepared by ESTCP.

Performance metrics of attributes derived from the collected data (e.g. discrimination results) will determine whether this demonstration ultimately meets its desired objective of successful discrimination performance for the MetalMapper cued-interrogation system.

Table 1 Performance Objectives/Metrics and Confirmation Methods

Performance Objective	Metric	Data Required	Success Criteria	Result achieved
Reliability and robustness	Operator feedback	• Field notes	Operator acceptance	**Partially MET** Some issues with Novatel SPAN
Survey rate	Number of targets visited per day	• Field notes	More than 200 per day	**MET** 204 per day 215 per day (excl short days)
Percent completed	Percentage of anomalies visited	• Field notes	Cued data obtained for all EM61 target picks	**MET** 100% of anomalies surveyed
Location accuracy	Distance between center of sensor and anomaly	• GPS location in collected groundtruth • MM position and IMU	MM center location within 30 cm of TOI at least 90% of the time	**MET** **(to within 1 cm)** 90% within 31 cm
Maximize correct classification of munitions.	Number of targets-of-interest retained.	• Prioritized anomaly lists, • Scoring reports from IDA,	Approach correctly classifies all targets-of-interest.	**MET** Pd = 100%
Maximize correct classification of non-munitions.	Number of false alarms eliminated.	• Prioritized anomaly lists, • Scoring reports from IDA,	Reduction of false alarms by > 75% while retaining all targets of interest.	**MET** 91% reduction in FA

Performance Objective	Metric	Data Required	Success Criteria	Result achieved
Specification of no-dig threshold.	P_{class} and N_{fa} at demonstrator operating point.	• Demonstrator-specified threshold. • Scoring reports from IDA.	Threshold specified by the demonstrator to achieve criteria above.	**MET** Pd = 100% 91% reduction in FA
Minimize number of anomalies that cannot be analyzed.	Number of anomalies that must be classified as "Unable to Analyze."	• Demonstrator target parameters.	Reliable target parameters can be estimated for > 90% of anomalies on each sensor's detection list.	**MET** 0% of anomalies were can't analyze

4.0SITE DESCRIPTION

4.1 SITE SELECTION

The Pole Mountain Target and Maneuver Area is a 62,448.15 acre site located near Laramie, Wyoming. The demonstration was conducted in the Bisbee Hill Maneuver Area. This site was chosen as the next in a series of sites for demonstration of the classification process. The first site in the series, former Camp Sibert in Alabama, had only one target-of-interest and item “size” was an effective discriminate. A hillside range at the former Camp San Luis Obispo in California was selected for the second of these demonstrations because of the wider mix of munitions, including 60-mm, 81-mm, and 4.2-in mortars and 2.36-in rockets. Three additional munitions types were discovered during the course of the demonstration. The third site chosen was the former Camp Butner in North Carolina. This site is known to be contaminated with items as small as 37-mm projectiles, adding yet another layer of complexity into the process. The fourth site, the former Mare Island Naval Shipyard (MINS) in Vallejo, CA, was selected because of an opportunity in the Navy’s remediation schedule at MINS to conduct the study in the midst of their ongoing munitions response project and prior to the upcoming removal action in 2012. The fifth site, Camp Beale in Yuba, CA, was selected for demonstration because it is partially wooded and is thought to contain a wide mixture of munitions.

This site was selected because of its wide mixture of munitions and variable terrain. The smallest known munition on the site is the 37-mm projectile, the largest known items are 3-inch projectiles and mortars, with a range of munition sizes in between.

Figure 6, extracted from the ESTCP Study Plan (Figure 4-2 in (ESTCP, 2011), outlines the demonstration site boundary, comprising 50 acres. A detailed description of the site, its history, and other useful details is contained in the ESTCP Study Plan (ESTCP, 2011).

4.2 SITE HISTORY

The PMTMA was established in 1879 as the Fort D.A. Russell Wood and Water Reserve. The land status alternated between national forest and military reservation from 1897 to 1925. The Pole Mountain area has also been known as the Crow Creek Forest Reserve, Fort D.A. Russell Target and Maneuver Range, Fort Francis E. Warren Target and Maneuver Range, Pole Mountain Reservation, Pole Mountain Training Annex, and Warren Training Annex. It was extensively used before 1959 as a target and maneuver area by the Army, the Reserve Officers’ Training Corps, the Citizens’ Military Training Corps, various National Guard units, and the Department of the Air Force.

4.3 MUNITIONS CONTAMINATION

A large variety of munitions have been reported as used at PMTMA. Physical evidence for the following items was discovered during the RI:

- Projectiles containing high explosive (HE) filler (37-mm to 155-mm, and 2.95-inch).
- Shrapnel projectiles (75-mm and 3-inch).

- 37-mm projectiles (inert and unfuzed).
- 3-inch Stokes mortars (practice, fuzed).
- 60-mm mortars containing HE filler.
- Small arms ammunition (.30-caliber and .50-caliber).

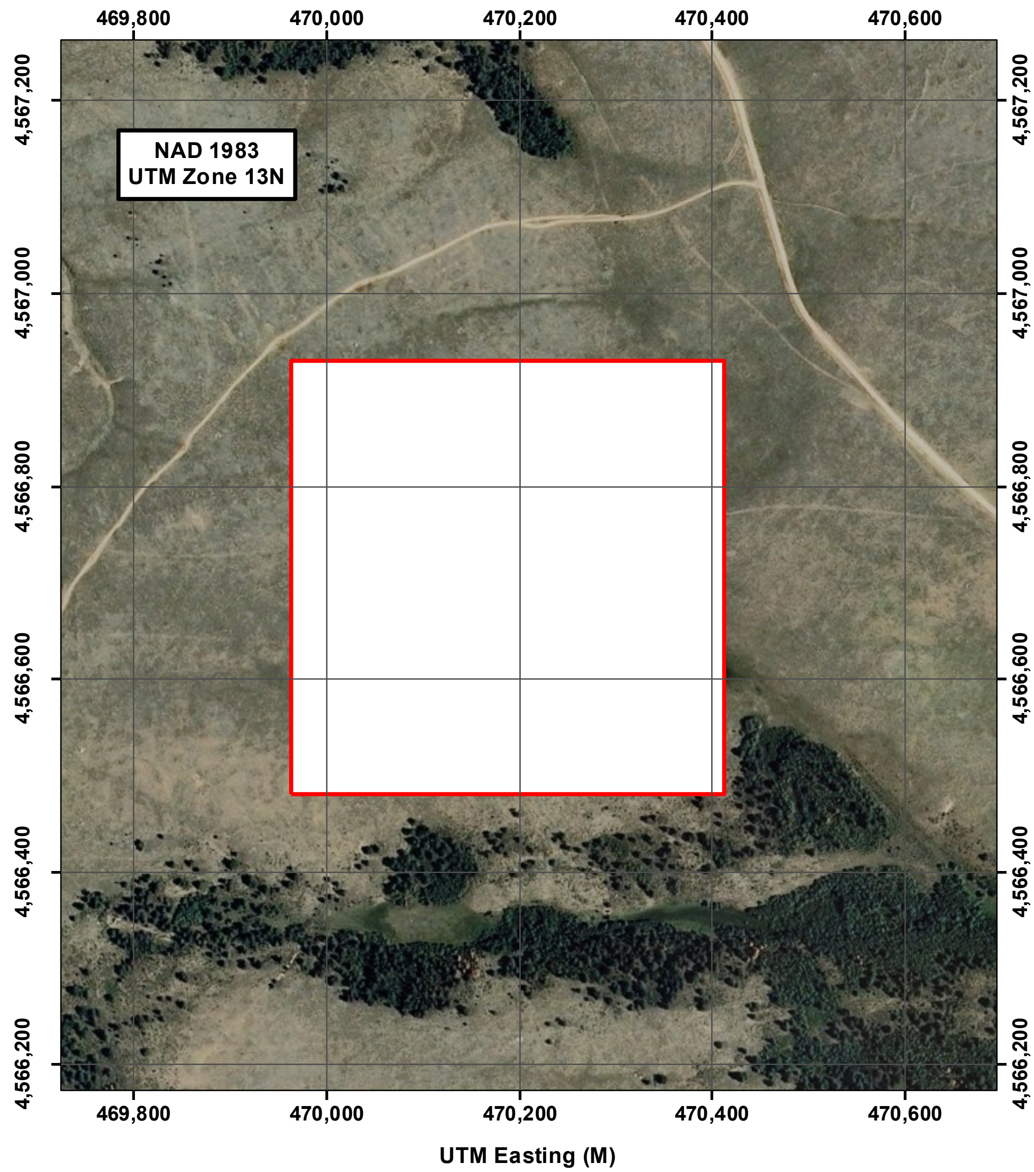


Figure 6 Final Demonstration Site Boundary (50 acres)

4.4 SITE GEODETIC CONTROL INFORMATION

The survey monuments in Table 3 were used for setting up the GPS base-station and verifying GPS rover position. Sky Research established the control points CP3 and CP4.

Table 2 List of Primary Survey Monuments

(Used for the surveying in UTM-Zone 16N, NAD-83)

Survey Monuments	Easting (m)	Northing (m)	Elevation (m)		
ESTCP1	4566072.102	471029.953	2454.650	3.5" ALUM DISC IN CONC.	Published value
ESTCP2	4566115.924	471090.253	2448.180	3.5" ALUM DISC IN CONC. "ESTCP2 2010"	Published value
CP3	4566553.883	468904.088	2524.249	1/8" RBR 1" PROUD OF GROUND SURFACE	Derived from 1 hour GPS observation post processed through NGS OPUS
CP4	4566537.402	468949.922	2523.396	TENT STAKE W/CTR PUNCH ADJACENT TO TEST PIT	Derived from 1 hour GPS observation post processed through NGS OPUS

5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The objective of this program is to demonstrate a methodology for the use of classification in the munitions response process. The three key components of this methodology are collection of high-quality geophysical data and principled selection of anomalous regions in those data, analysis of the selected anomalies using physics-based models to extract target parameters such as size, shape, and materials properties, and the use of those parameters to construct a prioritized dig list. This demonstration report predominantly addresses the data-collection aspect of the Pole Mountain demonstration, specifically the collection of cued-interrogation data.

5.2 PRE-DEMONSTRATION ACTIVITIES

The main ESTCP demonstration report for Pole Mountain (ESTCP, 2011) lists all the pre-demonstration activities conducted at the site including:

- Collection of historical records about the site through coordination with the Omaha District, US Army Corps of Engineers
- EM61 transects to define initial demonstration area
- Establishment of two first order navigation points to be used for all emplacement, data collection, and validation activities.
- Surface clearance of the site
- Development of a seed plan
- Establishment of an instrument verification strip near the demonstration area (Table 3).

Prior to mobilization to Pole Mountain, we spent approximately one week collecting cued-interrogation data over a test plot. This “shake-down test” allowed the field crew to become more familiar with the operation of the different instruments and in the correct operating procedure for the cued-interrogation surveys.

5.3 DATA COLLECTION PROCEDURES

5.3.1 Demonstration Set-Up and Start-Up

Sky Research deployed to Pole Mountain on July 20, 2011, and unpacked, assembled, and function checked equipment. Data collection (two cued points) started that day. The following general procedures were followed for each survey day:

- Morning brief and tailgate safety talk.
- GPS base station setup, GPS rover position check.
- MetalMapper setup and start-of-day equipment tests.
- Field check of start-of-day tests.
- Mobilization of MetalMapper to data collection area.

- For each cued point, the anomaly was surveyed using the procedure outlined in the next section.
- Throughout the survey day, a static background measurement was conducted at a nearby, metal-free location.
- End-of-day equipment tests.

We used a two person field crew. One operated the MetalMapper while the other processed/uploaded data and monitored weather conditions.

Table 3. Contents of the Instrument Verification Strip.

Item ID	Description	Easting (m)	Northing (m)	Depth (m)	Inclination	Orientation
T-001	Shotput	4566543.87	468927.18	0.30	N/A	N/A
T-002	Small ISO	4566543.77	468922.15	0.15	Horizontal	Across Track
T-003	Small ISO	4566543.67	468917.36	0.15	Horizontal	Along Track
T-004	37 mm	4566543.53	468912.37	0.15	Horizontal	Across Track
T-005	75 mm	4566543.504	468907.465	0.15	Horizontal	Across Track

5.3.2 Cued interrogation procedure

MetalMapper data were collected over 2,370 anomaly locations provided by the ESTCP Program Office using the acquisition parameters listed in Table 4. A mapping interface facilitated positioning of the sensor by displaying the sensor location relative to the cued anomaly coordinates. Once the sensor is within a few feet, the operator uses the real-time receiver cube response display to center the sensor over the object.

Average point to point transit and sensor centering time varied from 90 seconds to up to 3 minutes. Once at the point, data collection took less than 30 seconds.

The standardization and calibration tests described in the next section were conducted during each day of surveying.

Table 4 Acquisition Parameters: nRpts = Number of repeats, Win = Window, RxMode = Receiver Mode, TxMode = Transmitter Mode

Mode	Hold-Off Time (us)	Block Period (s)	nRpts	Win Width (%)	nStks	RxMode	TxMode
Static	50	0.9	27	10	10	DecayDecimated	ZYX

Triggering the MetalMapper transmit coil caused intermittent resetting of the IMU heading values. Commencing on the third day of data collection, the heading from a handheld compass was manually recorded as a backup to the IMU heading measurement.

5.3.3 Calibration activities

The following calibration activities were undertaken during the course of the survey:

- Twice-daily measurements of the IVS.
- Background measurements in a metal free area conducted at least twice per-day.
- Measurements of a number of test-objects in a shallow-test pit were completed at the start of the survey period. Each projectile was measured in multiple orientations and at two depths (10 and 20 cm to top of item). Items measured included:
  - 37 mm projectile
  - 57 mm projectile
  - 75 mm projectile (also at 30 cm depth)
  - Stokes mortar (also at 30 and 45 cm depths)
  - Calibration ball (single measurements at 10 and 20 cm)

5.3.4 Quality checks

Initial data validation for each anomaly was performed on-site by a member of the survey team. This processing was done to verify the integrity of the data collected and enabled any data problems to be immediately found and rectified. If questionable data were observed, they were uploaded to the project FTP site for immediate analysis by the project data processor.

5.3.5 Period of Operation

The field portion of this demonstration commenced on July 20, 2011, and was completed on August 5, 2011. A summary of activities on each day are provided in the table below, with a more detailed description provided in the field notes accompanying the data deliverable. The points per day in Table 8 refer to the number of points completed, and do not include multiple data shots due to poor positioning, multi-peak anomalies, etc.

5.3.6 Demobilization

At the end of field operations, all equipment, materials, and supplies were removed from the site and returned to Sky Research's office in Denver, Colorado.

5.3.7 Health and Safety Plan

A host organization exists for this demonstration site. All field work was conducted under the authority of the existing work plan. No separate Health and Safety Plan was required.

Table 5 Summary of On-Site Activities.

Day	Summary of activities	Approximate Points/Hr
July 20, 2011	Mobilize equipment from Denver, CO to the Pole Mountain project site. Unload, assemble and function check equipment. Check GPS base station and survey control. Collect test pit data and begin cued points.	7
July 21, 2011	Troubleshooting of Inertial Navigation System (INS) alignment problem. Collected limited cued data.	15
July 22, 2011	Collected cued data over 211 points, questionable heading values.	24
July 24, 2011	Collected cued data over 186 points. Began recording backup heading values as measured on a handheld compass.	22
July 25, 2011	Collected cued data over 201 points.	24
July 26, 2011	Collected cued data over 94 points, stopped early due to lightning.	13
July 27, 2011	Collected cued data over 154 points. Repaired fairlead on vehicle platform.	18
July 28, 2011	Collected cued data over 209 points, INS alignment stable for part of the day.	28
July 31, 2011	Collected cued data over 162 points, stopped early due to lightning. INS alignment stable for most of the day.	27
August 1, 2011	Collected cued data over 251 points. INS alignment stable for entire day.	28
August 2, 2011	Collected cued data over 247 points. INS alignment stable for entire day.	30
August 3, 2011	Collected cued data over 214 points, stopped early due to lightning. INS alignment stable for entire day.	33
August 4, 2011	Collected cued data over 316 points. INS alignment stable for entire day.	35
August 5, 2011	Collected cued data over 68 points and 80 recollects. Additional test pit data collected. INS alignment stable for entire day.	39
August 7, 2011	Packed up equipment, demobilized from project site back to Denver, Colorado.	

5.4 MANAGEMENT AND STAFFING

The responsibilities for this demonstration are outlined in Figure 7. Dr. Stephen Billings was the Principal Investigator (PI) for this project.

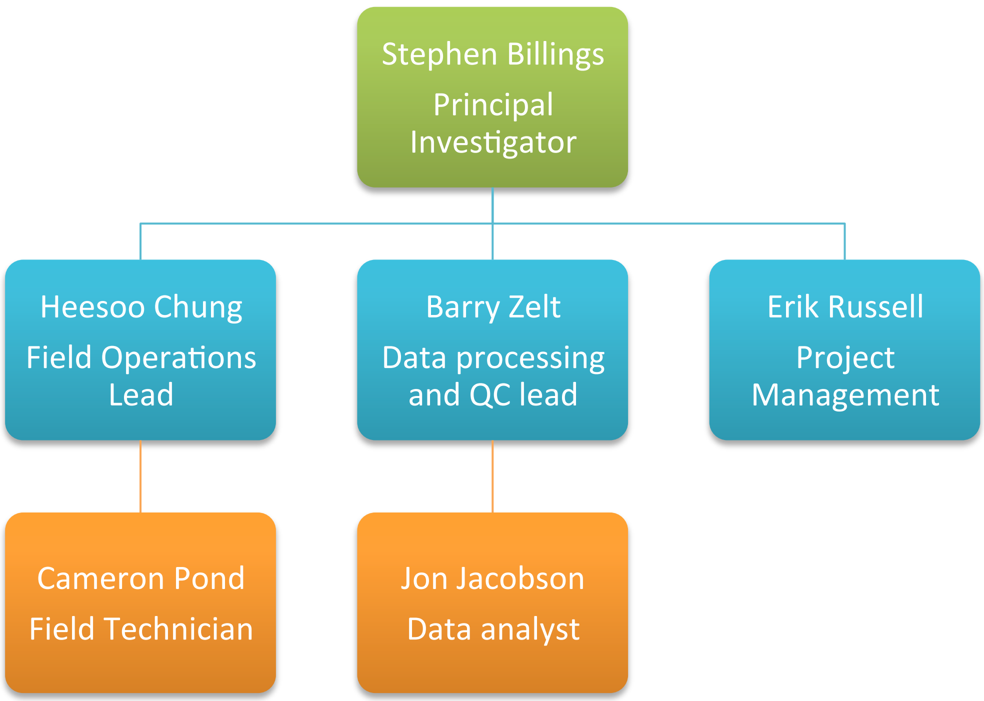


Figure 7 Management and Staffing Diagram

6.0 CALIBRATIONS, DATA PROCESSING AND ARCHIVING

6.1 PREPROCESSING

The following pre-processing steps were conducted.

- *Initial review of collected data:* Validate that metadata (point ID, heading) is correct.
- *Calculation of orientation:* Calculate the orientation of the MetalMapper sensor using IMU or manual compass heading.
- *Background removal:* Throughout the survey day, background data are recorded with the MetalMapper in a metal-free part of the survey area. For each recorded cued point, the background recorded from the closest measurement (in time) was subtracted from the MetalMapper receiver data.
- *Data conversion:* Data are converted into a .csv file format for analysis in Geosoft or UXOLab.

6.2 INITIAL QUALITY CONTROL

Each night an initial QC of the data was conducted by a QC analyst to determine if there were any problems with the data that would require any anomalies to be recollected. The QC review included comparing the location of the center of the MetalMapper against the location of the EM61 anomaly pick. Errors of larger than about a meter typically occurred when the MetalMapper measurement was associated in the field notes with the wrong EM61 anomaly. Usually, this mis-association occurred when the MetalMapper acquisition was either one point in front or behind the EM61 anomaly list, and affected several anomalies in a row. The problem was easily remedied by shifting the MetalMapper data up or down one target in the EM61 list.

Differences in location of less than 1 m were typically caused when the MetalMapper was not centered correctly over the buried item (e.g. Figure 8). If this occurred, the QC analyst would flag the anomaly for recollection and would communicate that information to the field-team. A total of 125 anomalies required recollection.

6.3 DAILY CALIBRATION RESULTS

The QC analyst also analyzed the twice-daily IVS data and compared the predicted and measured locations of each IVS item (Figure 9) as well as the principle axis polarizabilities (Figure 10). During the first two days, compass measurements were not taken and the IMU information was corrupt for a number of IVS measurements. This resulted in errors of 30 cm (or occasionally larger) in the IVS positions. Once compass measurements were taken and incorporated in the data processing the predicted IVS positions varied by less than 10 cm day to day and were typically biased about 5 to 12 cm to the South-West (Table 6).

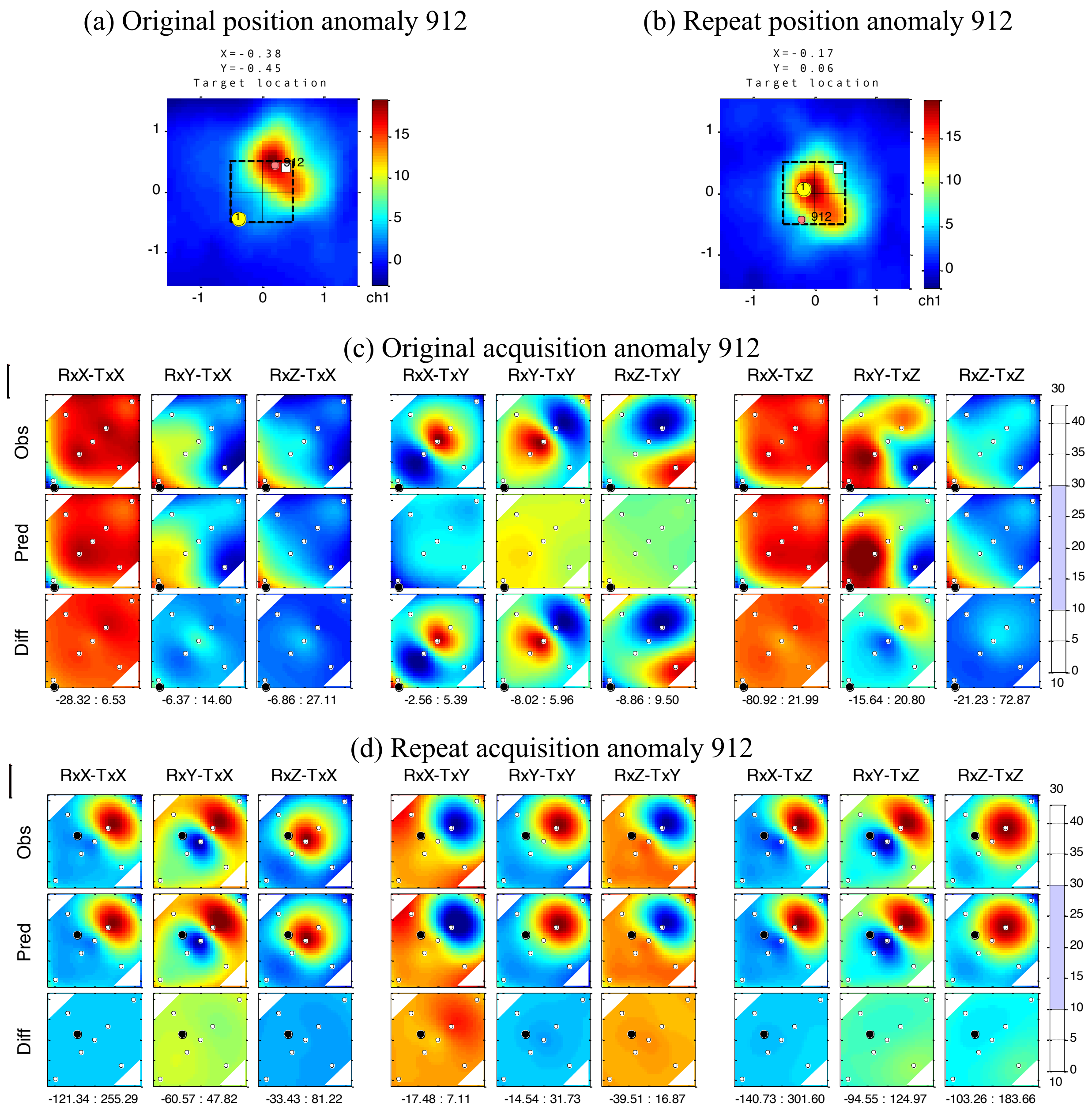


Figure 8. Example application of daily QC that identified a poorly centered MetalMapper acquisition. The top row shows the MetalMapper position of the original and recollected data against the EM61 anomaly map. The bottom two rows show the observed, predicted and residual MetalMapper data for the original (c) and recollected (d) locations.

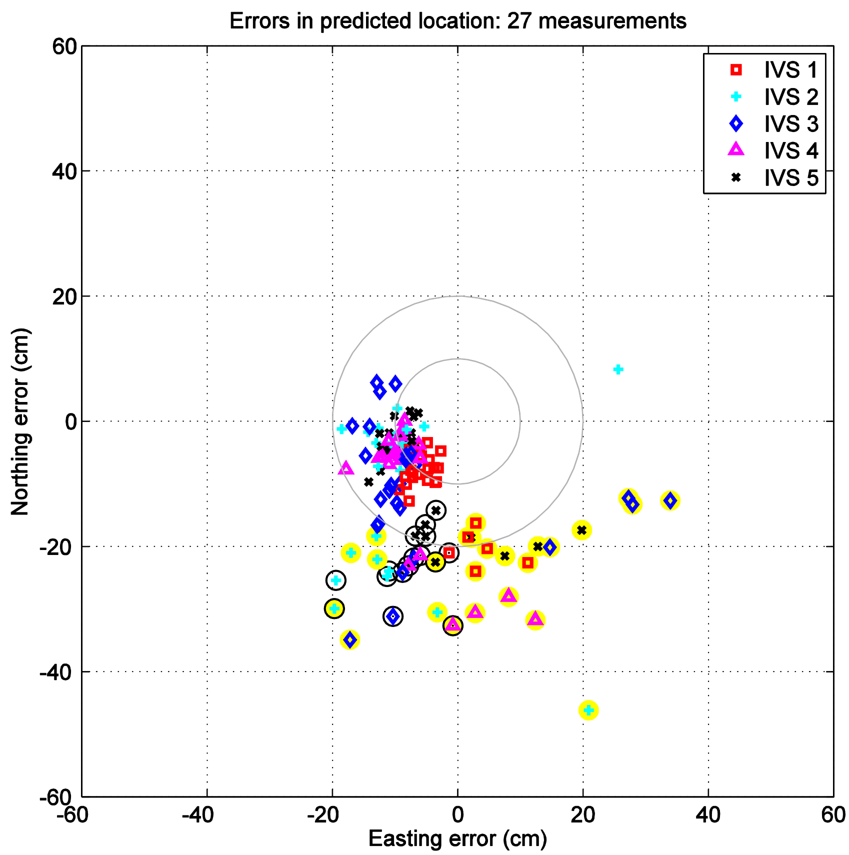


Figure 9. AM/PM Interpreted Location of the IVS Items. Items with a circle were collected without valid IMU data and those highlighted yellow had no compass measurement.

Table 6. Summary of location errors on the IVS items (excluding days without compass measurements).

Item ID	Description	RMS error Easting (cm)	RMS error Easting (cm)	Bias Easting (cm)	Bias Northing (cm)	Std Dev Easting (cm)	Std Dev Northing (cm)
T-001	Shotput	6.3	9.3	-5.9	-8.4	2.2	3.9
T-002	Small ISO	13.0	10.7	-9.2	-5.6	9.1	9.1
T-003	Small ISO	11.3	13.8	-10.9	-9.3	2.7	10.2
T-004	37 mm	10.0	6.8	-9.6	-5.2	2.7	4.4
T-005	75 mm	9.2	8.8	-8.7	-5.8	3.0	6.6
	Average	**10.0**	**9.9**	**-8.9**	**-6.9**	**3.9**	**6.8**

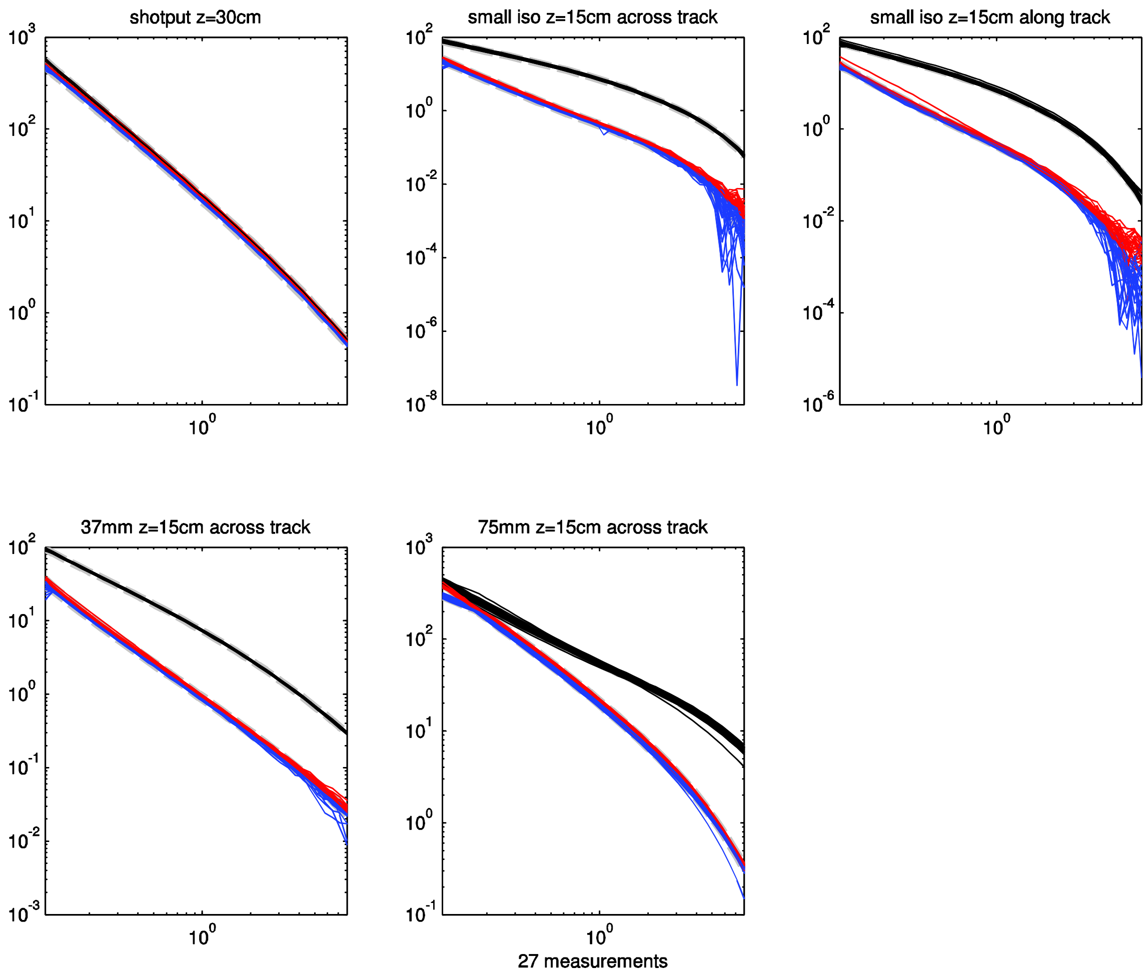


Figure 10. Polarizabilities extracted from 27 repeat measurements over the 5 IVS items.

6.4 DATA PRODUCTS

The MetalMapper data collected as part of this demonstration are available from the ESTCP Program Office. The data were arranged into three separate packages comprising

(1) The field data over the 2,370 targets identified at Pole Mountain;
(2) Measurements over the testpit (calibration ball and 37, 57 and 75 mm projectiles as well as a stokes mortar);
(3) All measurements made on the IVS strip (comprising a total of 27 repeats over each of the 5 IVS items).

6.4.1 Field data

Raw and background-corrected data in comma-separated value (CSV) files are provided in separate folders. The file naming convention is:

PM_Sky_NNNNN_D11dddStaticMMMMM_raw_NNNNN.csv (raw)

PM_Sky_NNNNN_D11dddStaticMMMMM_bc_NNNNN.csv (background-corrected)

where:

NNNNN is the anomaly number

ddd is the acquisition day number

StaticMMMMM is the MetalMapper source .tem file name

Anomaly numbers range from 1 through 2374; anomaly numbers 699, 718, 1110 and 1358 were not assigned.

Background-corrected files have been normalized by the transmitter current (average of the last 10 values reported in the raw CSV file) and have had the background noise subtracted from the data. During each day of data acquisition a number of measurements of the background noise were made at a magnetically quiet field site. One of these measurements was used for the background correction of all data from that same day. The background files are provided in a separate folder.

Due to unresolved issues with our IMU, the heading obtained from the IMU was deemed to be unreliable. In addition, the IMU would intermittently cut out, resulting in no orientation information for some anomalies. A handheld compass was used to obtain approximate heading information, but compass readings were not available for the first two days of data acquisition. The heading value that appears in the CSV files (for both raw and background-corrected data) represents the compass reading (corrected for local magnetic declination) when a compass reading exists. When no compass reading is available, the heading value is the value obtained from the IMU (if the IMU was functioning). Information on the availability of compass readings and IMU status is given in an accompanying file (PoleMtn_CSV_Log_File.xls) which lists, for each anomaly:

1. Anomaly number
2. Raw CSV file name
3. Background-corrected CSV file name
4. Background noise file used for background subtraction in (3)
5. Compass status: 1 if a compass reading was taken; 0 if a compass reading was not taken
6. IMU status: 1 if the IMU provided orientation information; 0 if it did not

6.4.2 Test-pit measurements

The data format is the same as for the field-data files. A list of the different ordnance, depth and orientation combinations collected are provided in an accompanying file (PoleMtn_CSV_Log_File_TestPit.xls).

6.4.3 Measurements on the Instrument Verification Strip

The data format is the same as for the field-data files. A list of the different IVS items and the 27 repeat measurements are provided in an accompanying file (PoleMtn_CSV_Log_File_IVS.xls).

6.5 PRODUCTION TEAM CLASSIFICATION METHOD AND RESULTS

The production team independently fit polarization tensor models and developed a digging order using tools developed under ESTCP MR-201004. Both single and multi-object polarization tensors models were fit to each anomaly and the fit results QC'd by the production team. Ground-truth information was requested for 32 items with three of the ground-truth anomalies corresponding to TOI (Table 7). Together with the test-pit items, the ground-truth was used to determine dig-list order using the DigZilla tool (Pasion et al., 2012). The DigZilla analysis used all three polarizabilities. An initial stop-dig point comprising 261 excavations was selected based on visual review of the data. All 157 remaining TOI were recovered with this stop-dig point, with the last TOI recovered on the very last dig. The production team used the automated method of Pasion et al., (2012) for determining the stop-dig point which resulted in an additional 74 digs, none of which ended up being TOI. A further 2 digs were added during subsequent QC and neither of these were TOI either (Table 7).

At the final stop-dig point (and including groundtruth), 369 anomalies were excavated and all 160 TOI were identified. A total of 209 of the 2210 clutter items were excavated: this meant that 91% of the clutter could have been left in the ground.

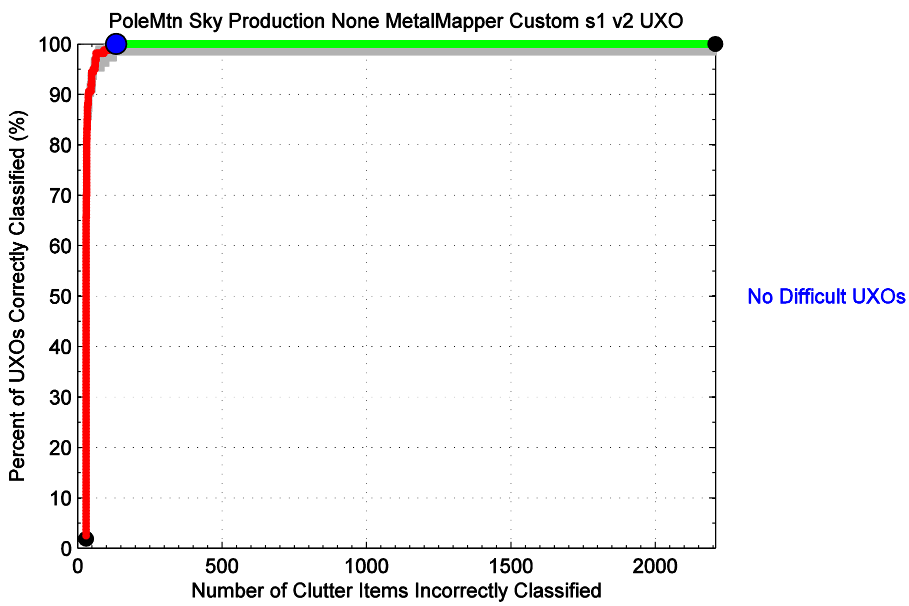


Figure 11. ROC curve for the dig-list submitted by the SKY production team.

Table 7. Number of excavations and TOI recovered in each of the 4 stages of submittals made by the SKY production team.

Stage	Number excavations	TOI recovered	TOI remaining
Training	32	3	157
Stage 1	261	157	0
Stage 2	74	0	0
Stage 3	2	0	0

7.0PERFORMANCE ASSESSMENT

7.1 PERFORMANCE CRITERIA

Table 1 listed the performance criteria for the demonstration. We now list each of the performance objectives and determine if they have been met.

7.1.1 Reliability and Robustness

Objective: General observations.

Performance: Partially Met.

With the exception of the INS alignment errors during the first part of the project, the data collection proceeded with few technical problems. Besides the INS alignment, the minor issues encountered were related to a young software platform. We expect issues such as point ID not recorded in the metadata, cart orientation display on map being off by 180 degrees or a lack of units on graphs to be worked out as the software matures.

The hardware platform performed adequately. Due to the stress associated with the mounting platform, speed was limited to 2mph on rough terrain, 3mph on rough dirt roads, and 5 mph on smooth dirt roads. Going from one point to the next required a minimum of three transmission shifts, with an average of eight shifts per cued point. While the existing platform can continue to be used, it does cause a lot of extra wear and tear on the vehicle.

7.1.2 Survey Rate

Objective: 200 anomalies / day.

Performance: Met.

Table 8 lists the number of anomalies that were surveyed each day. On average 205 anomalies were visited each survey day. The IMU related INS Alignment errors had a large impact on production rates. Time was lost both to troubleshooting the issue and in navigating to each anomaly which was difficult without heading information. Neglecting the bad IMU days, the average survey rate was 32 points per hour. This rate does not include GPS base stations setup time or transportation time. The rate does include down time during the survey day and time spent on taking multiple shots of the same point ID.

7.1.3 Percentage of Assigned Targets Completed

Objective: 100% as allowed by topography / vegetation.

Performance: Met, with 100% of targets surveyed with the MetalMapper.

Review of the collected data reveals that 100% of all cued-interrogation anomalies were surveyed. The vehicle platform was not able to go over obstacles higher than 14 inches. This was not a limiting factor at this site.

Table 8 Number of Cued-Interrogation Anomalies Surveyed Each Day

Day of Year	Date	Start Cued	End Cued	Field Time (hours)	Number of Point IDs	Number of Recollected Points	Total Field Shots (approx.)	Point IDs/Hour	Number of Test Pit Items	Number of Bad headings (approx.)	Other Notes
D11201	7/20/2011	1840	1900	0.3	2	3	5	6.7	46		Test pit day.
D11202	7/21/2011	1430	1600	1.5	23	1	24	15.3		24	Troubleshoot INS.
D11203	7/22/2011	812	1650	8.6	211	7	218	24.5		170	
D11205	7/24/2011	825	1704	8.5	186	9	195	21.9		26	Start recording compass headings.
D11206	7/25/2011	812	1643	8.5	201	5	206	23.6			Unknown number of bad IMU.
D11207	7/26/2011	841	1532	7	94	11	105	13.4			Unknown (high?) number of bad IMU, bad positioning day, light weather.
D11208	7/27/2011	710	1545	8.5	154	24	178	18.1			Unknown number of bad IMU, repair fairlead.
D11209	7/28/2011	849	1633	7.6	209	5	214	27.5			Unknown (low?) number of bad IMU.
D11211	7/30/2011	830	1420	6	162	3	165	27.0			Troubleshoot IMU (DL4 vs ProPak), stable IMU?
D11213	8/1/2011	740	1645	9	251	10	261	27.9			Good IMU.
D11214	8/2/2011	823	1634	8.1	247	3	250	30.5			Good IMU.
D11215	8/3/2011	741	1408	6.5	214	17	231	32.9			Good IMU, clutter field.
D11216	8/4/2011	730	1630	9	316	10	326	35.1			Good IMU, light weather.
D11217	8/5/2011	800	944	1.75	68	17	85	38.9			Good IMU.

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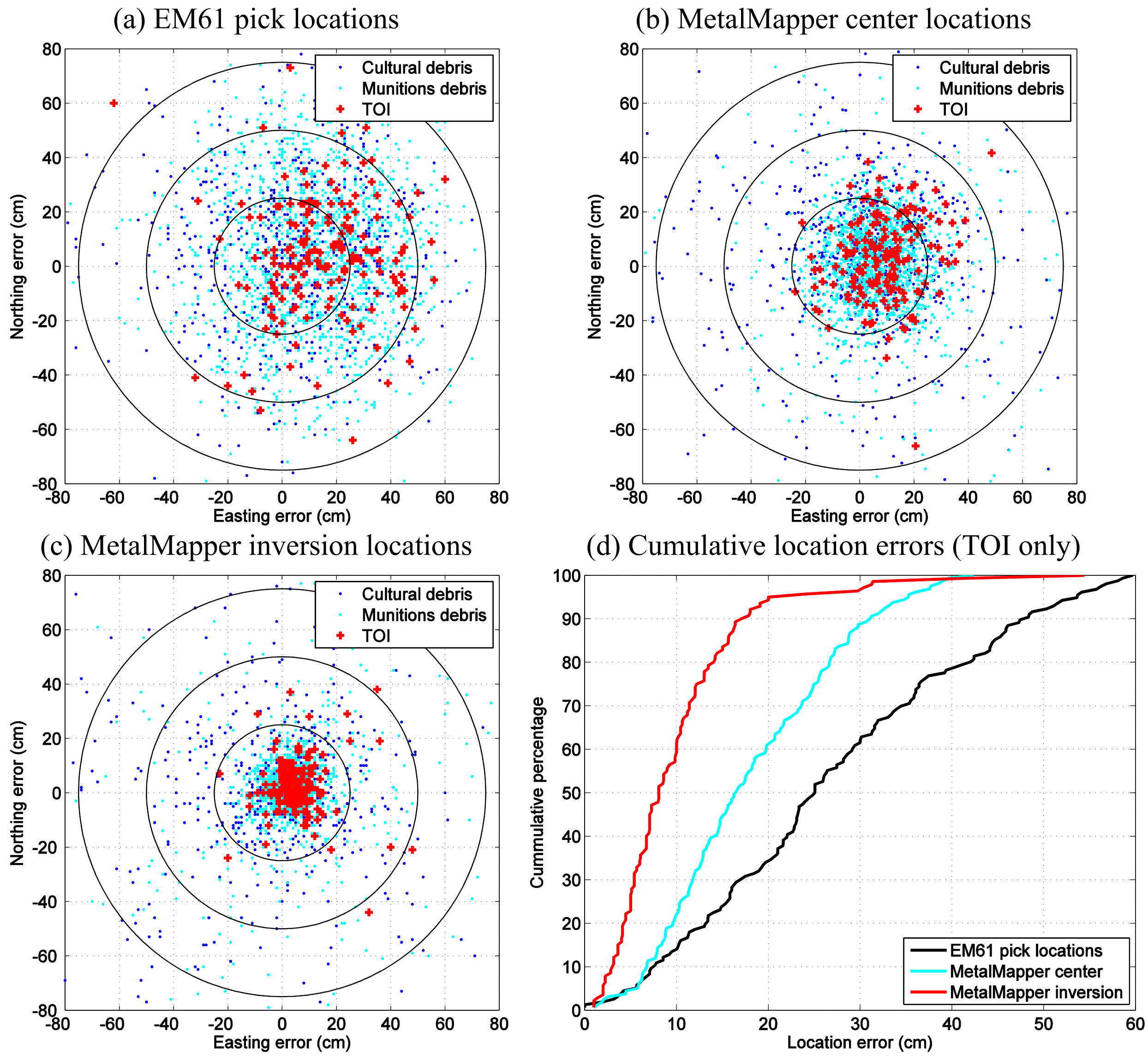

Figure 12. Location errors for (a) original EM61 pick location; (b) MetalMapper center location and (c) MetalMapper inversion location with 25 cm error circles shown. The cumulative error plot in (d) only considers TOI.

7.1.4 Location accuracy of interpreted anomalies

Objective: MetalMapper center location within 30 cm of TOI at least 90% of the time.

Performance: Effectively met, with the 90th percentile occurring at 31 cm

Previous work with the MetalMapper (Pasion et al., 2012) has shown that the ability to accurately constrain polarizabilities degrades if an anomaly is not well centered under the MetalMapper sensor. Figure 12a compares the EM61 pick location to the reported GPS position from ground-truth. In cases where more than one item and location was reported by the dig-team, then the item closest to the EM61 pick location is used. From inspection of this figure and the

cumulative location error plot in Figure 12d it is evident that placing the MetalMapper sensor directly over the EM61 pick location will result in many poorly centered anomalies.

At each location, the moving arrows display was used to center the MetalMapper array. Figure 12b and d demonstrate a significant improvement in anomaly centering relative to the EM61 pick locations. For TOI we did not quite reach our stated performance objective of 90% within 30 cm, with the 90^{th} percentile occurring 31 cm. For this analysis we retained all points including those with no compass measurement.

Figure 12c shows the location error of the polarization tensor model compared to the ground-truth location. 95% of all TOI were located with an accuracy of better than 20 cm.

7.1.5 Maximize correct classification of munitions.

Objective: 100% of TOI correctly identified

Performance: Met

The scoring analysis conducted by IDA indicated that all 160 TOI were found before the designated stop-digging point.

7.1.6 Maximize correct classification of non-munitions.

Objective: Greater than 75% reduction in non-TOI while retaining all TOI

Performance: Met

At the selected operating point, 91% of the non-TOI were left in the ground.

7.1.7 Specification of no-dig threshold.

Objective: All TOI recovered with 75% of non-TOI left in the ground

Performance: Met

At the selected operating point, all TOI were recovered with 91% of non-TOI left in the ground.

7.1.8 Minimize number of anomalies that cannot be analyzed.

Objective: Reliable target parameters can be estimated for > 90% of anomalies on each sensor's detection list.

Performance: Met

In the final interpretation, an acceptable model was fit to every single anomaly, so that there were zero "can't analyze" anomalies. To achieve this metric required rigorous daily QC and the recollection of 125 anomalies: or 5.2% of the total number of anomalies. Without this investment in QC and recollects, we would still have met the "can't analyze" metric of < 10%.

8.0 COST ASSESSMENT

8.1 COST REPORTING

Cost categories for this demonstration are mobilization, field survey, data analysis, demobilization, and reporting. These costs were tracked throughout the demonstration and are presented in Table 9 (fully burdened costs for the demonstration and the pre-mobilization tests conducted in Denver).

Table 9 Fully Burdened Costs

Categories	Pre-mob testing	Mobilization	Data collection	Data processing	Reporting	Total (excluding testing)	Total
Labor	$ 52,275	$ 31,621	$ 53,205	$ 9,208	$ 16,156		$162,465
Equipment	$ 8,478	$ 7,869	$ 34,534	$ -	$ -		$ 50,882
Travel	$ 4,162	$ 1,148	$ 5,872	$ -	$ 342		$ 11,524
Matls and Supplies	$ 91	$ 550	$ 738	$ -	$ -		$ 1,379
Std ODCs	$ 2,798	$ 2,245	$ 3,402	$ 452	$ 929		$ 9,825
Total	$ 67,805	$ 43,433	$ 97,750	$ 9,659	$ 17,428		$236,075

8.2 COST ANALYSIS

During the Pole Mountain demonstration MetalMapper data were collected at 2,370 anomaly locations. Based on the cost information presented in Table 9 the per anomaly costs (excluding mobilization and reporting) were

- $41.24 for data collection; and
- $4.08 for data processing.

The total cost per anomaly (for data collection and processing) was $45.52.

Using an often quoted rule of thumb that each excavation costs $100, then without deploying the MetalMapper system the excavation costs would have been approximately $237,000. With the MetalMapper only 369 anomalies needed to be excavated at a cost of $36,900. When combined with the MetalMapper mobilization, data collection, processing and reporting costs of $168,270 the cost of clearance using the MetalMapper was $205,170: a saving of $31,830 (or 13%).

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9.0 POINTS OF CONTACT

ESTCP

Herb Nelson	Program Manager, MM	Tel: 703-696-8726 Cell: 202-215-4844 Herbert.Nelson@osd.mil
Katherine Kaye	Program Assistant, MM	Tel: 410-884-4447 Fax: 703-478-0526 kkaye@hgl.com

Sky Research, Inc.

Stephen Billings	Principal Investigator	Tel: 720-306-1165 stephen.billings@skyresearch.com